

Explaining the observed deviation in $R(D^{(*)})$ in an anomalous 2HDM.

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Abstract

The reported combined excess of about 4σ , by BABAR, Belle and LHCb, in the measurements of $R(D^{(*)})$ and $\text{Br}(B \rightarrow \tau \nu_\tau)$ than expected from the standard model constitute the most significant discrepancy from the standard model in collider experiments thus far (apart from the non zero neutrino masses). In this work we analyze the phenomenological implications for these decay modes in a Flipped/Lepton-Specific two-Higgs-doublet model with anomalously enhanced charged Higgs coupling to τ/b . When experimental and theoretical errors are added in quadrature, we conclude that this extension of the standard model can give results in agreement within 1σ of the experimental values for the combination of $R(D^{(*)})$ and $\text{Br}(B \rightarrow \tau \nu_\tau)$ data.¹

Introduction

It has been reported first by Babar[2] and Belle[3], a possible hint of lepton flavor universality violating NP in $R(D^{(*)}) = \frac{\text{Br}(B \rightarrow D^{(*)} \tau \nu)}{\text{Br}(B \rightarrow D^{(*)} l \nu)}$. And recently LHCb[4] has also measured a deviation in $R(D^*)$ from SM. The combined (Babar, Belle and LHCb) results gives[5]

$$\begin{aligned} R(D)_{EXP} &= 0.388 \pm 0.047 \\ R(D^*)_{EXP} &= 0.321 \pm 0.021 \end{aligned} \tag{1}$$

Comparing these measurement with the SM predictions[6]

$$\begin{aligned} R(D)_{SM} &= 0.297 \pm 0.017 \\ R(D^*)_{SM} &= 0.252 \pm 0.003 \end{aligned} \tag{2}$$

there is a deviation of 1.8σ for the $R(D)$ and 3.3σ for the $R(D^*)$ and the combination corresponds close to a 3.8σ deviation from SM prediction. It is further supported by measurement of $\text{Br}(B \rightarrow \tau \nu)$ by Babar[7] and

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Belle[8] and gives(from PDG average):

$$Br_{EXP}(B \rightarrow \tau\nu) = (1.14 \pm 0.27) \times 10^{-4} \quad (3)$$

which is 1.3σ above the SM prediction[9]. Now if we add the errors in $R(D^*)$ and $B(B \rightarrow \tau\nu)$ in quadrature then the three data combined deviates from SM by about 4σ . In this analysis we examine Higgs mediated flavor universality violation in a Flipped or Lepto-Specific 2HDM with anomalous charged Higgs coupling to τ lepton or b quark respectively. This work is base on the materials contianed in the reference [1].

Why simple 2HDM cann't explain it?

The effect of Physics beyond the SM in Taunic B decays has been studied extensively, particular in the context of Type-II 2HDM but Babar[2] has ruled out Type-II 2HDM at 99.8 percent confidence level from the fits to the $R(D^{(*)})$ data for any values of $\frac{\tan\beta}{M_{\pm}}$. How ever Belle's measurements shows some comparability with Type-II 2HDM at about $\frac{\tan\beta}{M_{\pm}} = 0.5 GeV^{-1}$ but if we include the $B \rightarrow \tau\nu_{\tau}$ data also then it turn out contribution from such a large $\frac{\tan\beta}{M_{\pm}}$ actually pushes the $B \rightarrow \tau\nu_{\tau}$ well over 5σ from the PDG world average. This is mainly due to the fact that since Type-I and Type-II 2HDMs interfere destructively with SM, in these type of 2HDMs only a large contribution from purely charged Higgs can have positive contribution from these models, but a large contribution from purely charged Higgs part that gives a moderate push to the $R(D^{(*)})$ pushes the $B \rightarrow \tau\nu_{\tau}$ beyond 5σ from the world average very fast. So only a 2HDM with constructive interference with SM like Flipped or Lepton specific 2HDM may be able to fit all three of the B-physics data $R(D^{(*)})$ and $B \rightarrow \tau\nu_{\tau}$. But Flipped or Lepton specific 2HDM in itself does not fit because in these models the $\tan\beta$ dependence between m_b and m_{τ} in the interference between SM and charged Higgs cancels out and so there is no corresponding increase in contribution from interference part as $\tan\beta$ increases. To fit all three of the data we need to modify these models so that there is some extra enhancement in interference part.

Modifying the Yukawa sector of Flipped/Lepto-Specific 2HDM.

In general 2HDM the Yukawa lagrangian is given as [10]:

$$\begin{aligned} \mathcal{L}_{Yukawa}^{2HDM} = & - \sum_{f=u,d,l} \frac{m_f}{\mathcal{V}_0} (\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i \xi_A^f \bar{f} \gamma_5 f A) \\ & - [\frac{\sqrt{2}V_{ud}}{\mathcal{V}_0} \bar{u}(m_u \xi_A^u P_L + m_d \xi_A^d P_R) d H^+ + \frac{\sqrt{2}\xi_A^l m_{\tau}}{\mathcal{V}_0} \bar{\nu}_L l_R H^+ + H.c] \end{aligned} \quad (4)$$

As mentioned in the previuos section, the interference from just Lepton specific or Flipped 2HDM turn out to be too small to fit the three data simultaneously since the $\tan\beta$ dependence between m_b and m_{τ} cancels out in these models although they gives constructive interference with SM unlike Type-I and Type-II 2HDM. Some additional factor has to be introduce into these models so that it can fit the three data. One simplest and straight forward way to achieve this enhancement is if we require that τ lepton is screened from interacting with the full strength to the Higgs VEV v_2 and to all the neutral excitations from Higgs vacuum like the scalars h , H^0 and the pseudo-scalar A^0 in Flipped 2HDM. Since the Yukawa sector of the τ lepton breaks the $SU_L(2)$ symmetry the theory is not renormalizable in itself, so it has to be embed inside a larger model in which Flipped 2HDM

comes out as a 400GeV-Few TeV scale effective theory. The details of how such an anomalous interaction can be embed inside a larger model is out side the scope of the present work and will be assigned to a future work. Here we focus on the phenomenological consequences of such a screening on observed B decay anomalies. Now since τ lepton is screened from seeing the full depth of v_2 , its Yukawa coupling must increase so that its mass which is proportional to $Y_{Yukawa} \times \frac{v_2}{\eta}$ now is the same as the observe mass m_τ , which will effectively enhance the Yukawa coupling of τ lepton to the charged Higgs by a factor of η while Yukawa coupling of τ to h , H^0 and A^0 remains same as in usual Flipped 2HDM as the η factors in the neutral scalar Yukawa interaction cancels out with that of the η factor coming from reduced higgs vacuum \mathcal{V}_0 . For same analysis carried out in the Lepton Specific 2HDM, see the comments at the end. Then the ξ_A^f factors in the charged Higgs interactions in this anomalous Flipped 2HDM with the screening factor η is given by:

$$\xi_A^u = \cot \beta, \xi_A^d = \tan \beta, \xi_A^{e,\mu} = -\cot \beta, \xi_A^\tau = -\eta \cot \beta. \quad (5)$$

Finally the charged Higgs lagrangian contributing to $b \rightarrow cl\nu$ in this model can be written in the most general form using Yukawa couplings derived from ξ_A^f s will be given as:

$$\mathcal{L}_{H^\pm}^{Yukawa} = -[V_{cb}\bar{c}(g_s + g_p\gamma_5)bH^+ - \bar{\nu}_l(f_s^l + f_p^l\gamma_5)lH^+ + H.C] \quad (6)$$

where

$$g_s = \frac{(m_b \tan \beta + m_c \cot \beta)}{\sqrt{2}\mathcal{V}_0}, g_p = \frac{(m_b \tan \beta - m_c \cot \beta)}{\sqrt{2}\mathcal{V}_0},$$

and

$$f_s^{e,\mu} = f_p^{e,\mu} = \frac{m_{e,\mu} \cot \beta}{\sqrt{2}\mathcal{V}_0} \text{ and } f_s^\tau = f_p^\tau = \frac{m_\tau \cot \beta}{\sqrt{2}\mathcal{V}_0} \eta.$$

Note the relative negative sign between the hadronic current and leptonic current which will ensure constructive interference between SM and charged Higgs contributions. In this model, SM and charged Higgs interfere constructive unlike Type-I and Type-II 2HDM models where they interfere destructively. In this modified Flipped 2HDM, the charged Higgs coupling to τ is enhanced by a factor of η than that of a simple Flipped 2HDM.

Results

Although the η is an independent parameter but if we require that $\eta = \tan^2 \beta$, then it leads to very simple interpretation of the results. If we require $\eta = \tan^2 \beta$, then the Yukawa interactions in the hadronic sector of our model has the same form as in the Type-II 2HDM but interaction in the leptonic sector of our model has the same form as in Flipped 2HDM except the τ lepton coupling to the charged Higgs, which has same form as in Type-II 2HDM but with opposite sign. Now there are only two parameters to fit i.e $\tan \beta$ and M_\pm , and a χ^2 analysis with the $R(D^{(*)})$ and $\mathcal{B}r(B^- \rightarrow \tau^- \nu_\tau)$ as data points to find the best fits for the parameters $\tan \beta$ and M_\pm gives $\chi_{min}^2 = 10.95$ for $M_\pm > 400$ GeV. This $M_\pm > 400$ GeV constrain is from $B \rightarrow X_s \gamma$ and for an estimate on the lower bound of M_\pm from $B \rightarrow X_s \gamma$ is given in [11]. We have tabulated for three different values of the parameters that fits at same accuracy in the table below:

S.no	$\tan \beta$	M_{\pm} GeV	$R(D)_{Th}$	$R(D^*)_{Th}$	$Br_{Th}(B \rightarrow \tau \nu)$
1	39.98	400	0.348	0.255	1.29×10^{-4}
2	69.97	700	0.348	0.255	1.29×10^{-4}
3	99.95	1000	0.348	0.255	1.29×10^{-4}

Table 1: $\chi^2_{min} = 10.95$ and we have restricted the $\tan \beta$ in the range of $100 > \tan \beta > 1$.

As the data in the table above and combine errors from experiments given in Eqs(1) and Eqs(3) shows, in the range $1 \text{ TeV} \geq M_{\pm} \geq 400 \text{ GeV}$ and $100 > \tan \beta > 1$, we have:

$$R(D)_{Th} = 0.348 \pm 0.16 \quad (7)$$

$$R(D^*)_{Th} = 0.255 \pm 0.07 \quad (8)$$

and

$$Br_{Th}(B \rightarrow \tau \nu) = (1.29 \pm 0.89) \times 10^{-4} \quad (9)$$

compared to the combined[Babar,Belle,LHCb][5] experimental values:

$$R(D)_{EXP} = 0.388 \pm 0.047 \quad (10)$$

$$R(D^*)_{EXP} = 0.321 \pm 0.021 \quad (11)$$

and

$$Br_{EXP}(B \rightarrow \tau \nu) = (1.14 \pm 0.27) \times 10^{-4} \quad (12)$$

Conclusions

Babar, Belle and recently LHCb has reported an excess in the measurements of $R(D^*)$, $R(D)$ and $Br(B \rightarrow \tau \nu_{\tau})$ than expected from SM, a possible signature of lepton flavor universality violating NP. In this work we have analyzed the implications for these decay modes in a Flipped 2HDM with enhanced Yukawa coupling of H^{\pm} to τ lepton. By adding theoretical and experimental errors in quadrature from Eqs(7,8,9) and Eqs(10,11,12), we conclude that our phenomenological model can give results in agreement within 1σ deviation for the combination of $R(D^{(*)})$ and $Br(B \rightarrow \tau \nu_{\tau})$ compare to about 4σ deviation from SM from the latest combined[Babar,Belle,LHCb] experimental data for these observables.

The same results can be achieved if b quark replaces the τ lepton in a Lepton Specific 2HDM. In that case Yukawa coupling of the leptonic sector will be same as Type-II 2HDM and Yukawa coupling of the quark sector will be same as Lepton Specific 2HDM[10] except the b quark which will have the effective Yukawa coupling same as in Type-II with opposite sign and in that case, charged Higgs mass may be allowed to be lower than 400 GeV and for a recent work on muon g-2 in Lepton Specific 2HDM and related bounds see [12]. From the form of the Yukawa couplings it is expected that if we require $\eta = -1$ for the b quark or τ lepton in the 2HDM-II, then also it will fit the three datas at about same accuracy as above model of Flipped/Lepton-Specific 2HDM. This is interesting in a sense that it will be like 2HDM-II but with a wrong sign in either b quark or τ lepton Yukawa coupling, an anomalous SUSY.

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